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August 1993

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Waterways Experiment Station

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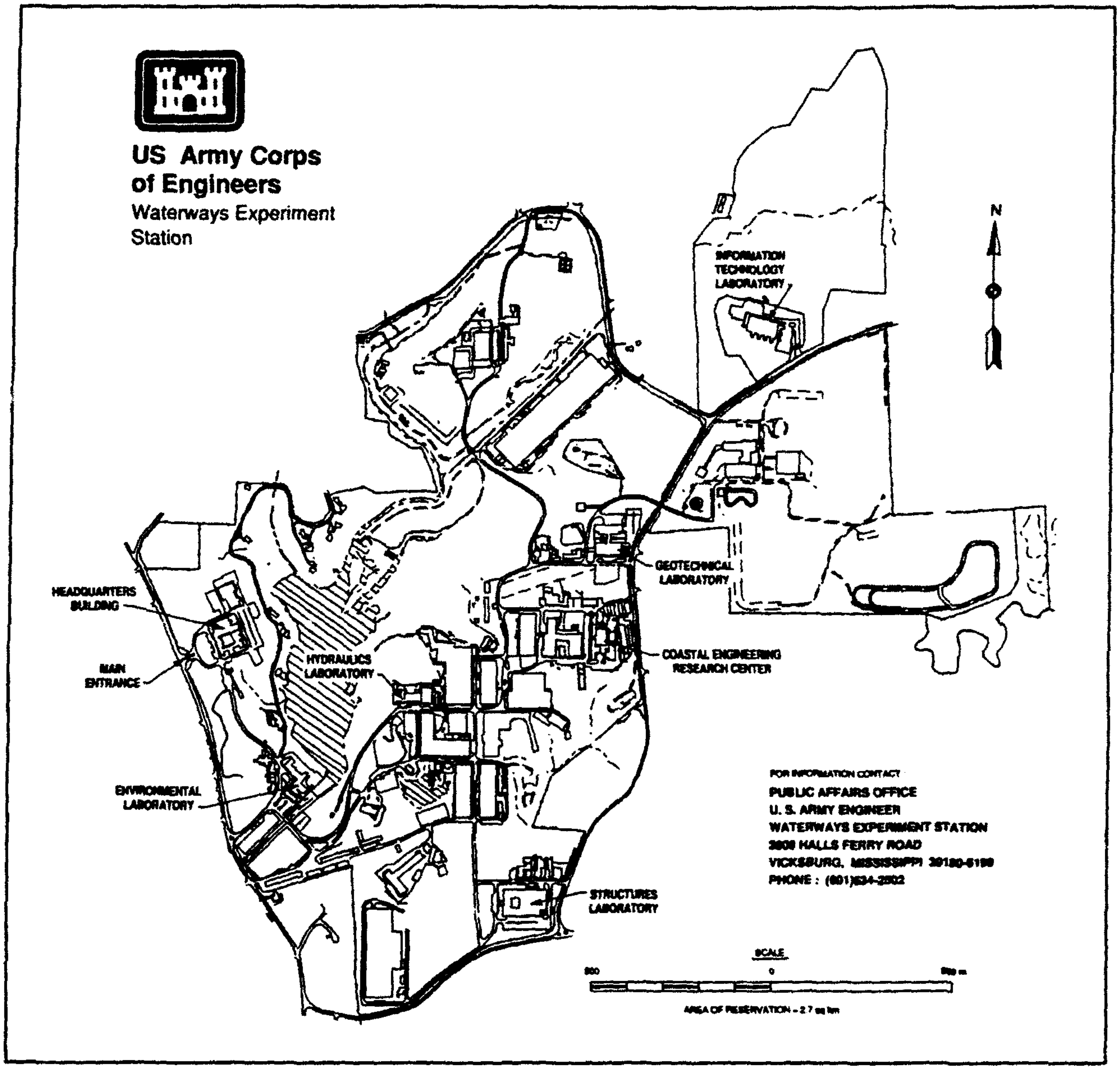

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Contents

Preface

The study described herein was performed at the Hydraulics Laboratory of the U.S. Army Engineer Waterways Experiment Station (WES) from October 1991 to July 1992 for Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Flood Control Structures Research Program. Funds were allotted under Civil Works Investigation Work Unit 32542, "River Bend System Hydraulics, Imposed Force Component." The HQUSACE Program Monitor was Mr. Thomas E. Munsey. Program Manager was Dr. Bobby J. Brown, Hydraulic Analysis Branch, Hydraulic Structures Division, Hydraulics Laboratory (HL). This study was accomplished under the direction of Messrs. F. A. Herrmann, Jr., Director, HL; R. A. Sager, Assistant Director, HL; and G. A. Pickering, Chief of the Hydraulic Structures Division, HL. The analysis was conducted by Dr. S. T. Maynord, project engineer, Spillways and Channel Branch, Hydraulics Structures Division, and Mrs. L. C. Hubbard, Math Modeling Group, Waterways Division, HL, under the direct supervision of Mr. N. R. Oswalt, Chief of the Spillways and Channels Branch. This report was written by Dr. Maynord and Mrs. Hubbard.

Messrs. Charlie Elliot, David Biedenharn, and John Brooks of the U.S. Army Engineer Division, Lower Mississippi Valley, provided the Mississippi River data used herein and vital review comments as the study progressed.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters

1 Introduction

Background

Knowledge regarding the distribution of velocity in rivers and channels is required in several areas of engineering including channel stability and protection, sediment transport, navigability, structure design, and structure performance. This study focuses on velocity for use in channel stability and protection with emphasis on bank protection. Specifically, the variation of depth-averaged velocity near concave bank lines is investigated. This study attempts to provide relatively simple techniques that require a small computational effort because the majority of bank protection designs cannot justify large expenditures of time and money for determination of design velocities.

Various techniques are available for determination of velocity distribution in rivers and channels and include physical models, numerical models, analytical models, and empirical methods. Two- and three-dimensional numerical models are available for defining the entire flow field in open channels. Two-dimensional models normally have not considered the effects of secondary currents, and velocities are underestimated at the outer bank of channel bends. Bernard (1990) has developed modifications to two-dimensional depth-averaged models that incorporate the effects of secondary currents. Both two- and three-dimensional models require computational effort beyond that justified for most bank protection projects. One-dimensional water-surface profile models that break up the cross section into different subsections based on depth and/or roughness do not properly account for the effects of secondary currents in bends and should be used only in straight reaches. Several analytical models have been developed including Engelund (1974), Ikeda, Parker, and Sawai (1981), Bridge (1982), Odgaard (1989), and Johannsen and Parker (1989). Empirical methods generally relate the nearbank velocity to the average channel velocity for ease of application since the designer frequently knows only the average channel velocity.

Objective and Scope

The objective of this study is to evaluate empirical methods for estimating nearbank velocities in river bends. This study expands on a study of Thorne

and Abt (1990) by analyzing a large body of velocity data obtained on the Mississippi River.

2 Basic Equation

The previous empirical efforts to predict the velocities along a bank line have related the nearbank velocity to the average channel velocity V_{avg}. The California Division of Highways (1970) uses the relation

$$\frac{V_{bank}}{V_{avg}} = C_1 \tag{1}$$

where

V_{bank} = maximum bank line velocity in the bend
C_1 = 2/3 for tangent velocity in straight reach
= 4/3 for impinged velocity in channel bends

Schmitt[1] recommends a value for C_1 of 0.7 for straight reaches and 1.2 for outside of bends. The U.S. Army Engineer District, Seattle, has used a value of C_1 of 1.5-2.0 for the outside of channel bends. Maynord (1988) found C_1 to be 1.5 for bend flows based on data taken by Blodgett and McConaughy (1986).

The use of Equation 1 has the following drawbacks:

a. Bank line velocity is not defined as surface, bottom, or depth averaged. If velocities are to be used in a riprap design procedure such as Engineer Manual (EM) 1110-2-1601 (Headquarters, U.S. Army Corps of Engineers (HQUSACE)), velocities should be depth averaged.

b. The location of the bank line velocity is not specified relative to a known point. Velocity needs to be specified as some fixed percentage of the distance from the toe to the waterline because the velocity changes rapidly with distance from the bank. Depth-averaged velocity

[1] R. W. Schmitt. (1981). "Brief discussion of average, bottom, and bank velocities in stream flow," File Report, U.S. Army Engineer District, Pittsburgh.

at 20 percent of the slope length up from the toe V_{ss} is used in the riprap design procedure in EM 1110-2-1601.

c. Other factors are not accounted for such as bend radius, channel width, bend angle, side slope angle, channel type or cross section, and aspect ratio (width/average depth). All of these factors are lumped into the coefficient C_1.

The primary advantages of Equation 1 are its ease of application and the fact that C_1 probably does not vary widely for typical bends having a radius/width ratio of 2 to 3, an aspect ratio greater than 20, a bend angle greater than 90 deg, and side slopes from 1V:1.5H to 1V:3H.

Thorne and Abt (1990) presented data that have been replotted in Plate 1 for estimating the depth-averaged velocity over the toe of the slope. Data from natural channel bends having straight and meandering approach channels are shown in Plate 1 along with Thorne and Abt's curve for straight approach channels. Instead of being a constant, Thorne and Abt present C_1 as a function of radius/width and the approach channel type. Thorne and Abt's data tend to verify the V_{bank}/V_{avg} versus R/W relationship where R is the center-line radius of the bend and W is the water-surface width.

EM 1110-2-1601 (HQUSACE 1991) presents guidance for determining outer bank velocity at 20 percent up the slope from the toe in natural and trapezoidal channels as shown by the curves in Plate 2. Plate 2 is based on data provided in Thorne and Abt (1990). Both Equation 1 and Plates 1 and 2 predict the maximum velocity in the bend. This study will evaluate Equation 1 and Plate 2 using data from the Mississippi River (river miles (RM) 587.2 to 327.8).

3 Analysis of Data

Data Source

The potamology survey carried out on the Mississippi River from 1966 to 1972 by the U.S. Army Engineer District, Vicksburg, supplied the data used in the analysis. The study reach extends from Smith Point Terrene (RM 602.8) to Bougere (RM 324.0). The information was found in hydrographic surveys and books containing the potomology discharge and sediment data. The potomology books are kept on file at the U.S. Army Engineer Division, Lower Mississippi Valley.

Choice of Bends and Discharges

Only those bends with continuous revetments were used. Revetments consisted of articulated concrete mattress placed from low water out past the toe of slope. Smith Point, for example, was not considered, as the outer bankline was interrupted by one tributary, one distributary, and one abandoned channel. Bends were also discarded if dikes were present on the outer bank and influenced the flow or if the flow patterns were too complex because of the presence of several channel bars.

Occasionally, a bend may have had only one section where the velocity had been noted, and these data were not included in the analysis. It was unlikely that the single section represented the maximum velocity in the bendway. To reduce data reduction requirements, similar discharges in the same bend were not repeated.

Dominant or effective discharge concepts relate to the discharge that best correlates with the size and form of the channel. The dominant discharge on the Mississippi River reach used herein is on the order of 1,000,000 cfs.[1] Velocities that were measured at discharges less than the effective discharge were taken in a channel that was formed predominantly by the previous

1 A table of factors for converting non-SI units of measurement to SI units can be found on page v.

sequence of high discharges. Preliminary plots using all measured data showed that some of the highest ratios of V_{bank}/V_{avg} were for lower discharges. Since most bank protection design flows are equal to or greater than the dominant or effective discharge, only those flows close to the effective discharge will be used in the analysis. Discharges were limited to 750,000 cfs or greater.

The data collected totalled 39 discharges spread over 15 bends. Table 1 provides a narrative based on all of the observed discharge records, many of which were not used in the analysis because the discharge was less than 750,000 cfs. Table 1 gives a summary of the bends used, their location, data source, and a description of some of the bend features. The bold type in the remarks column refers to features that will always be present in the bend from that date onward. At the first appearance of dikes on the inside of the bend the date was noted.

Data Recorded for Each Bend

Two types of parameters were noted for each bend and included those specific to the bend and those related to the velocity data taken at spaced sections around the bend. All the sections located on the revetted reach of the bend were used. If outer bank scour persisted downstream of the bend on the revetted bank and a velocity section was available at that point, it was included. The following data were recorded:

a. Data that apply to the whole bend and were extracted from the hydrographic survey:

(1) **Name** of the revetment.

(2) The **Entrance** and **Exit** points of the bend given in river miles. Entrance and exit points were assumed to coincide with the velocity ranges. If additional analyses were conducted with bend length as a parameter, the entrance and exit points should be redefined independent of the velocity range. The bend limits were positioned by looking at the plan view of the bend. This procedure was carried out as it is the one most likely used by other workers and because detailed cross-sectional data are not always available to allow the entrance and exit points to be identified by the shape of the cross section.

(3) The **Survey Sheets** and **Dates** for each discharge.

(4) **Remarks** about the bend. For example, if dikes were present, their number and position were noted; extensions made to the revetment were commented upon; or if a channel bar appeared, its location was reported.

(5) **The Radius of Curvature and Arc Angle**, which were obtained using a template. The radius of curvature was taken from the mid-channel line. If a channel bar was present, then the main flow channel next to the outer bank was used, as it was considered to be more representative of what was being studied.

b. Data specific to the cross sections.

(1) Data taken from the hydrographic surveys:

(a) **Section Location** in river miles.

(b) **The Distance from the Water's Edge to the Toe** measured directly off the map.

(2) Data taken directly from the potomology books.

(a) **Width**

(b) **Total Area**

(c) **Total Discharge**

The velocity reading consisted of three variables, **Distance** from the bank to the velocity reading, **Depth**, and **Velocity**. The velocity points were included if the ratio of the distance at which they were taken from the waterline x over distance from the waterline to the toe s was less than 2.5 (Figure 1). This region defines the nearbank zone as used in this report. The velocity data were obtained with a Price current meter using standard stream gaging techniques. Velocities were observed at a single point at or near 0.4 depth from the bottom to define the depth-averaged velocity. Any deviation from 0.4 depth was corrected by applying a standard adjustment factor. Velocities were also adjusted for angle of flow to obtain the velocity component perpendicular to the velocity range. Horizontal position of the boat was determined by range boards on-line at the section and sextant angle to a distant shore target.

Primary Data Analysis

The primary data were analyzed and plotted along with the derived parameters of average channel velocity, average depth, and radius of curvature over width. This produced 39 working plots of side slope velocity versus distance from the waterline. An example of the working plot is shown in Plate 3. These working plots are available from the authors but should be used with caution because they contain some basic differences regarding definition of width and average channel velocity from the main channel width and velocity

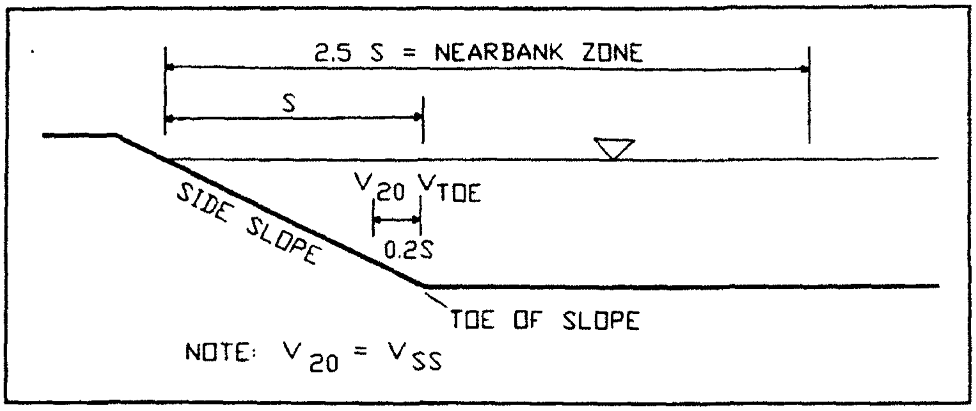

Figure 1. Schematic of nearbank zone

used in the final analysis presented in this report. The legend provides widths, depths, average velocity, R/W, etc., at the individual sections. To determine the maximum velocity in the bend at 20 percent up the slope from the toe V_{20} in this bend, interpolate between the points at each section at 20 percent up the slope from the toe to determine V_{20}/V. Plate 3 yields ratios of 0.88, 1.15, and 1.20 for sections 476.6, 476.0, and 475.2, respectively. These ratios are then multiplied by the average channel velocity shown for each section to obtain V_{20} of 0.88(4.85) = 4.3, 1.15(6.21) = 7.1, and 1.20(6.59) = 7.9 fps. The maximum velocity in the nearbank zone V_{nb} for the Fitler Cottonwood 5 bend would be 1.37(6.59) = 9.0 fps.

The side slope velocity plot was interpolated for the maximum velocity at 20 percent up from the toe. V_{20} was selected because it is used as the characteristic velocity for riprap sizing in EM 1110-2-1601. The maximum nearbank velocity was also determined from the working plots. The bend discharge shown in Table 2 was the average of all sections in the bend. The range of variables obtained can be seen in the following tabulation:

Variables	Lowest Value	Highest Value
Average discharge, cfs	756,560	1,348,840
Max V_{20}, fps	4.9	9.8
Max V_{nb}, fps	6.2	12.4
Arc angle, deg	26	185
Radius, ft	5,200	25,500

The basic data set is shown in Table 2, and only discharges used in the analysis are shown therein.

Water-surface width on the Mississippi River varies widely from large values at the entrance to the bend to relatively small values at or near the exit

to the bend. Consequently the representative width is difficult to define. Since width is difficult to define, aspect ratio (width/average depth) is also hard to define. The width and average channel velocity shown in Table 2 represent the main channel only in the region of the bend entrance and upstream crossing. At the discharges close to effective discharge used herein, some of the cross sections at the crossing/entrance region have wide, shallow regions on one or both sides of the channel. These wide, shallow regions, if included, will result in overestimation of the effective channel width and underestimation of the average channel velocity in the *R/W* versus V_{bank}/V_{avg} plots. In sections not having shallow regions adjacent to the channel, the width and average velocity of the entire channel were recorded in Table 2. For channels with shallow regions, the main channel width used herein was equal to the minimum width that passes 95 percent of the total discharge as shown in Figure 2. For channels with shallow regions, the average channel velocity in the main channel was equal to the average channel velocity in the minimum width channel described previously. Even if midchannel bars were present, the main channel width in the entrance/crossing region was used as the representative width.

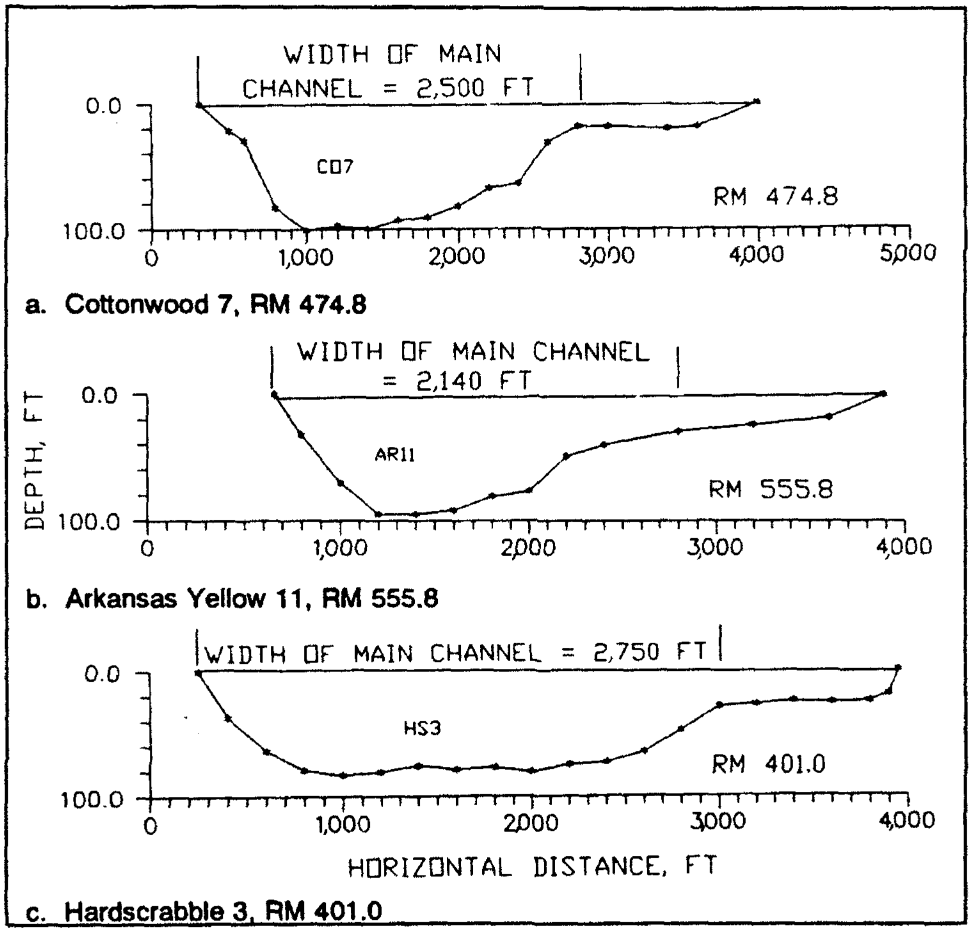

Figure 2. Channel widths based on main channel discharge = 95 percent of total discharge

A semilog plot of radius of curvature over main channel width versus the ratio of the maximum velocity at 20 percent over the main channel average velocity is shown in Plate 4. Also shown is the curve for natural channels from Plate 2.

Plate 5 presents maximum nearbank velocity over main channel average velocity versus R/W for all bends. A curve having V_{ss}/V_{avg} that is 25 percent greater than the curve for natural channels from EM 1110-2-1601 (Plate 2) was found to provide an upper limit of the data and is shown on Plate 5.

Thorne and Abt (1990) found that the approach channel of a bend was important and that different results were obtained if the bend was a single isolated bend or a consecutive bend of a meandering river. A few of the 15 bends appeared to have straight entrance reaches, but they were found to be too short (1 - <4 widths long), and no distinction based on approach channel was attempted in this analysis.

The data were then divided into two categories based on the position of the V_{20}/V_{avg} values relative to the curve from EM 1110-2-1601. Grand Gulf, Kentucky, Cottonwood, Prentiss, Arkansas Yellow, and Lake Karnac revetments fell well below the curve from EM 1110-2-1601 as shown in Plate 6. The other nine bends were much closer to the design curve as shown in Plate 7. A detailed classification was then applied having five categories: (a) bends that had a relatively uniform radius and were free from channel bars, (b) bends that had large midchannel bars that went their entire length, (c) channel bars that appeared toward the inside bank, (d) revetments with irregular bank line alignment, and (e) irregular alignment and bars present. The following tabulation lists the bends in each category:

Uniform Radius, No Bars	Big Mid-Channel Bars	Channel Bars Toward Inside Bank	Irregular Alignment Revetments	Irregular Alignment and Bars Present
Catfish Point	Kentucky	Cypress	Arkansas Yellow	Prentiss
Mayersville		Walnut Point	Fitler Cottonwood	
Cottonwood		Belle Island	Hardscrabble	
Milliken			Bougere	
Lake Karnac				
Grand Gulf				

This classification and Plates 6 and 7 provided no insight as to the scatter exhibited in Plate 4. There was no apparent reason why the six bends in Plate 6 fell well below the design curve. Even though the physical channel parameters did not appear to be the cause, the reason these points fall well below the design curve is generally because V_{20} and V_{nb} are very low for

these bends. A plot of V_{20}/V_{avg} versus R and V_{nb}/V_{avg} versus R also scattered, showing that width is not the culprit.

Arc angle was evaluated and provided no consistent explanation of the variation of V_{20}/V_{avg} or V_{nb}/V_{avg} in Plates 4 and 5.

The scatter observed in Plates 4 and 5 remains unresolved and is probably due to several factors.

a. At the top of the list is the fact that while these bends exhibit some similarities in plan view, each bend has distinctive, site-specific features that can cause large variations. This can be particularly true along bank lines where local irregularities impact significantly on velocities in the nearbank zone. These variations made it difficult to assign a representative radius, width, arc angle, etc., to each bend.

b. Variables other than those used in Plates 4 and 5 are the controlling factors in defining maximum bend velocities. It is also possible that short-term fluctuations of velocity are adding to the scatter in the data.

c. While the data were collected using standard methods by the same personnel, also contributing to the scatter is the uncertainty associated with data taken over a 6-year period using different velocity meters under a variety of environmental conditions.

d. Variations in water temperature throughout the year cause changes in flow resistance because of changes in bed forms. Variation may also have been caused by velocities at some bends having been taken on the rising side of the hydrograph and others taken on the falling side of the hydrograph.

The comparison of the data in Plate 4 with the curve from Plate 2 for V_{20}/V_{avg} does not provide any information about the slope of the line, but the relationship is sufficiently conservative for Mississippi River bends because only 2 of the 39 points fall well above the EM 1110-2-1601 curve.

An analysis of all the data was conducted to determine what value of C_1 in Equation 1 should be used if all factors (such as R/W) are lumped into C_1. The analysis resulted in the following:

Ratio	C_1	Percentage of Data Equal to or Less Than
maximum V_{20}/V_{avg}	1.6	92
maximum V_{nb}/V_{avg}	1.8	95

It should be noted that the maximum nearbank velocity is not necessarily the maximum velocity in the bend.

4 Summary and Conclusions

The Mississippi River data used herein exhibit significant scatter due to a variety of factors. The most important of these are the many factors that cause bends to be distinct and site-specific.

The maximum riprap design velocity V_{20} in a bend was equal to or less than $1.6V_{avg}$ in 92 percent of the data. The maximum velocity in the near bank zone was equal to or less than $1.8V_{avg}$ in 95 percent of the data.

Variation in V_{20}/V_{avg} due to arc angle could not be determined with the Mississippi River data. Variation in V_{20}/V_{avg} due to a classification of bend types based on channel bars was also inconclusive.

When riprap is being designed for the Mississippi River or similar systems, the relationship used in EM 1110-2-1601 for V_{20}/V_{avg} versus R/W is applicable based on comparison with the Mississippi River data.

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Table 1
Summary of Bends Used in Analysis

Revetment Name	Bend Location RM	Survey Sheet	Date[1]	Remarks
Prentiss 1	587.2 to 581.8	Terrene Ozark	3/11-14/68	**Arkansas River joins inside bank at 583.3.** Channel bar near outside bank not mapped all the way around 585.5-584.3. Midchannel bar 582.5-581.5.
2			4/25/68-5/1/68	Large channel bar toward outside bank 585.5-584.4. Small midchannel bar at 582.0-581.4
3			6/5-11/68	**Two dikes present on inside bank 585.7-584.0.** Channel bar toward outside bank 585.4-584.4.
4			8/28/68-9/3/68	Channel bar toward outside bank at 584.1—not surveyed all the way around. Channel bar opposite, near inside bank 585.1-584.6.
5			10/16-22/68	Channel bar toward outside bank at 584.2 not surveyed all the way around. Dikes are dry.
6			2/18-25/69	Channel bar toward outside bank at 585.4-584.4.
7			7/29/69-8/6/69	Channel bar toward outside bank at 585.5-584.5. Channel bar near inside bank 584.6-583.8.
8			9/18-29/69	Channel bar toward outside bank not mapped all way round, ends 584.3. Islands are present where Arkansas River joins. Dikes are dry.
9			5/2-11/67	Channel bar toward outside bank at 585.6-584.5. Small midchannel bar 582.4-582.0.
10			5/8-14/70	Channel bar toward outside bank 585.45-584.5.
Catfish Point 1	576.0 to 572.0	Ozark Eutaw	9/4-16/68	
2			1/10-13/67	
3			3/13-17/67	Very shallow flow over Point Bar, some readings missing.
4			10/23-29/68	
5			3/10-12/69	Slight flow behind point bar 574.4-573.2.
6			4/24-30/69	Flow over point bar.

(Sheet 1 of 6)

[1] Dates not in chronological order.

Table 1 (Continued)				
Revetment Name	**Bend Location RM**	**Survey Sheet**	**Date**	**Remarks**
Catfish Point 7	576.0 to 572.0	Ozark Eutaw	9/30/69-10/2/69	
8			6/24/71-7/6/71	Flow behind point bar, no readings--ignored it.
9			3/15-22/72	Flow just about covering point bar.
10			10/24-28/66	
11			5/31/67-6/9/67	Flow over point bar.
12			3/27/68-4/5/68	
13			5/14-19/70	
14			8/14-25/70	
Cypress 1	572.0 to 567.0	Ozark Eutaw	1/10-13/67	Slight flow behind and over inside channel bar 568.2-568.7.
2			3/13-17/67	
3			9/4-16/68	
4			10/23-29/68	Inside channel bar has flow behind it 570.8-569.3
5			3/10-12/69	Midchannel bar 569.6-569.1. So small, ignored it.
6			4/24-30/69	Extra section included as deep spot downstream.
7			9/30/69-10/2/69	Midchannel bar 570.4-568.6. Smaller bar at 568.2-567.4 with no flow behind it.
8			6/24/71-7/6/71	Midchannel bar 569.9-568.1.
9			3/15-22/72	Small midchannel bar 569.2-568.8.
10			10/24-28/66	
11			5/31/67-6/9/67	
12			3/27/68-4/5/68	Revetment extended from 569.95 to 570.7.
13			5/14-19/70	
14			8/14-25/70	Midchannel bar 570.0-568.0.

(Sheet 2 of 6)

Table 1 (Continued)

Revetment Name	Bend Location RM	Survey Sheet	Date	Remarks
Arkansas City Yellow Bend 1	555.8 to 552.8	Choctaw Bar	4/24/67-5/5/67	Data includes extra section downstream, as only two sections in bend.
2			7/17-20/67	
3			8/28/67-9/1/67	
4			9/5-8/67	
5			11/8-16/67	
6			2/5-9/68	
7			3/18-26/68	
8			6/12-19/68	
9			9/9-13/68	
10			2/26/69-3/4/69	
11			4/30/69-5/6/69	
12			10/2-9/69	
13			5/19-22/70	
14			8/26/70-9/1/70	
15			7/6-13/71	
16			3/22-31/72	
Walnut Point 1	523.0 to 520.8	Kentucky Bend	6/26/67-7/7/67	Velocity data in Cracroft-Carolina book, not Kentucky Bend book. Five dike series inside bank 524.2 to 522.9. Channel bar toward inside bank 522.7-521.35.
2			10/16-19/67	Flow not touching dikes. Shallow flow inside bank not surveyed 523.0-522.5.
3			6/11-18/68	Midchannel bar toward inside bank 522.7-521.4.
4			2/14-19/69	Midchannel bar toward inside bank 522.5-521.4
5			5/28/69-6/4/69	Midchannel bar toward inside bank 522.7-521.4.
6			2/9-11/71	Flow not touching last two dikes.

(Sheet 3 of 6)

Table 1 (Continued)

Revetment Name	Bend Location RM	Survey Sheet	Date	Remarks
Walnut Point 7	523.0 to 520.8	Kentucky Bend	3/29/71-4/2/71	Midchannel bar toward inside bank 522.7-521.4. **Two dikes inside bank 520.6 & 519.8.**
8			9/9-14/71	Flow not touching dikes upstream, only just touching downstream ones.
Kentucky 1	519.6 to 516.2	Kentucky Bend	6/26/67-7/7/67	Small midchannel bar 519.7-519.3. Big midchannel bar 519.3-515.6.
2			10/16-19/67	Bar not fully mapped 520.0-515.0.
3			6/11-18/68	Big midchannel bar 519.1-515.6.
4			2/14-19/69	Big midchannel bar 518.7-515.55.
5			5/28/69-6/4/69	Big midchannel bar 519.2-515.4.
6			2/9-11/71	**Two dikes 520.6 & 519.8**, bar 520.0-519.4. Midchannel bar 519.4-513.0.
7			3/29/71-4/2/71	Midchannel bar 519.25-515.35.
8			9/9-14/71	Flow behind bar not fully surveyed, 519.9-514.9.
Mayers-ville 1	500.2 to 497.2	Carolina Baleshed	9/25-28/67	
2			4/25/68-5/1/68	Point bar with slight flow behind it 498.4-496.2.
3			3/6-8/68	
4			7/3-10/68	
5			9/30/68-10/3/68	**Dikes inside bank 500.6 and 500.0.**
6			2/21-25/69	Flow behind point bar 498.2-496.3.
7			6/6-10/69	Small channel bar toward inside bank 498.9-499.3.
8			7/9-15/70	**Revetment extended July 70 from 499.15 to 49[illegible] 75.**
9			2/23/71-3/2/71	Channel bar toward inside bank 498.2-496.3.
Fitler Cottonwood 1	479.0 to 475.2	Ajax Cottonwood	11/21-24/67	Slight bar close to outside bank 477.2 - 477.0.
2			5/7-10/68	
3			10/9-10/68	

(Sheet 4 of 6)

Table 1 (Continued)				
Revetment Name	**Bend Location RM**	**Survey Sheet**	**Date**	**Remarks**
Fitler Cottonwood 4	479.0 to 475.2	Ajax Cottonwood	3/21-25/69	Slight bar toward outer bank 477.2-477.0.
5			4/18-23/69	
6			12/5-8/69	
7			3/15-18/71	
8			7/30/71-8/2/71	Shallow section inside bank, no readings 477.6-476.0.
9			6/4-9/70	
Cotton-wood 1	474.8 to 472.8	Ajax Cotton-wood	11/21-24/67	
2			5/7-10/68	
3			10/9-10/68	
4			3/21-25/69	
5			4/18-23/69	
6			12/5-8/69	
7			3/15-18/71	
8			7/30/71-8/2/71	
9			6/4-9/70	
Belle Island 1	463.6 to 458.8	Cotton-wood-Belle Island and Belle Island- Milliken Bend	10/14-15/68 10/16-21/68	Channel bar toward inside bank 462.2-461.1.
2			12/11/69 12/12-15/69	Midchannel bar 462.0-460.95.
3			4/13-14/70 4/15-22/70	
4			1/19-20/71 1/21-27/71	
5			5/22-23/68 5/24-27/68	Slight scour hole outside bank 460.0.
Milliken 1	458.4 to 455.0	Belle Island-Milliken Bend	10/16-21/68	
2			12/12-15/69	
3			4/15-22/70	
4			1/21-27/71	

(Sheet 5 of 6)

Table 1 (Concluded)				
Revetment Name	**Bend Location RM**	**Survey Sheet**	**Date**	**Remarks**
Milliken 5	458.4 to 455.0	Belle Island-Milliken Bend	5/24-27/68	Scour hole outside bank 454.8, but rest of channel deeper. Little bar near inner bank 455.9-455.7—ignored it.
Lake Karnac 1	422.8 to 418.2	Point Pleasant	1/9-21/70	Shallow area outside bank between entrance and apex.
2			7/16-24/70	Shallow area outside bank dry - makes bend tighter.
3			9/28/70-10/6/70	Shallow area outside bank dry - makes bend tighter.
4			3/10-18/71	
5			5/12-27/71	Shallow area has flow behind it—bar 422.0-421.4.
6			11/29/71-12/15/71	
Grand Gulf 1	405.8 to 401.6	Grand Gulf	3/31/70-4/3/70	
2			10/14-19/70	
3			3/19-23/71	
4			12/15-21/71	
Hard-scrabble 1	401.0 to 397.0	Grand Gulf	3/31/70-4/3/70	
2			10/14-19/70	
3			3/19-23/71	
4			12/15-21/71	
Bougere 1	331.6 to 327.8	Bougere	1/28/71-2/4/72	**Width downstream much narrower than upstream. Narrow point inside bank at 328.6-328.4.** Scour hole outside bank 328.8.
2			6/22-28/72	Some readings missing in midchannel 329.8-330.8. Scour hole 328.8-328.2.
3			12/6-13/72	Scour hole outside bank 328.8-328.2.

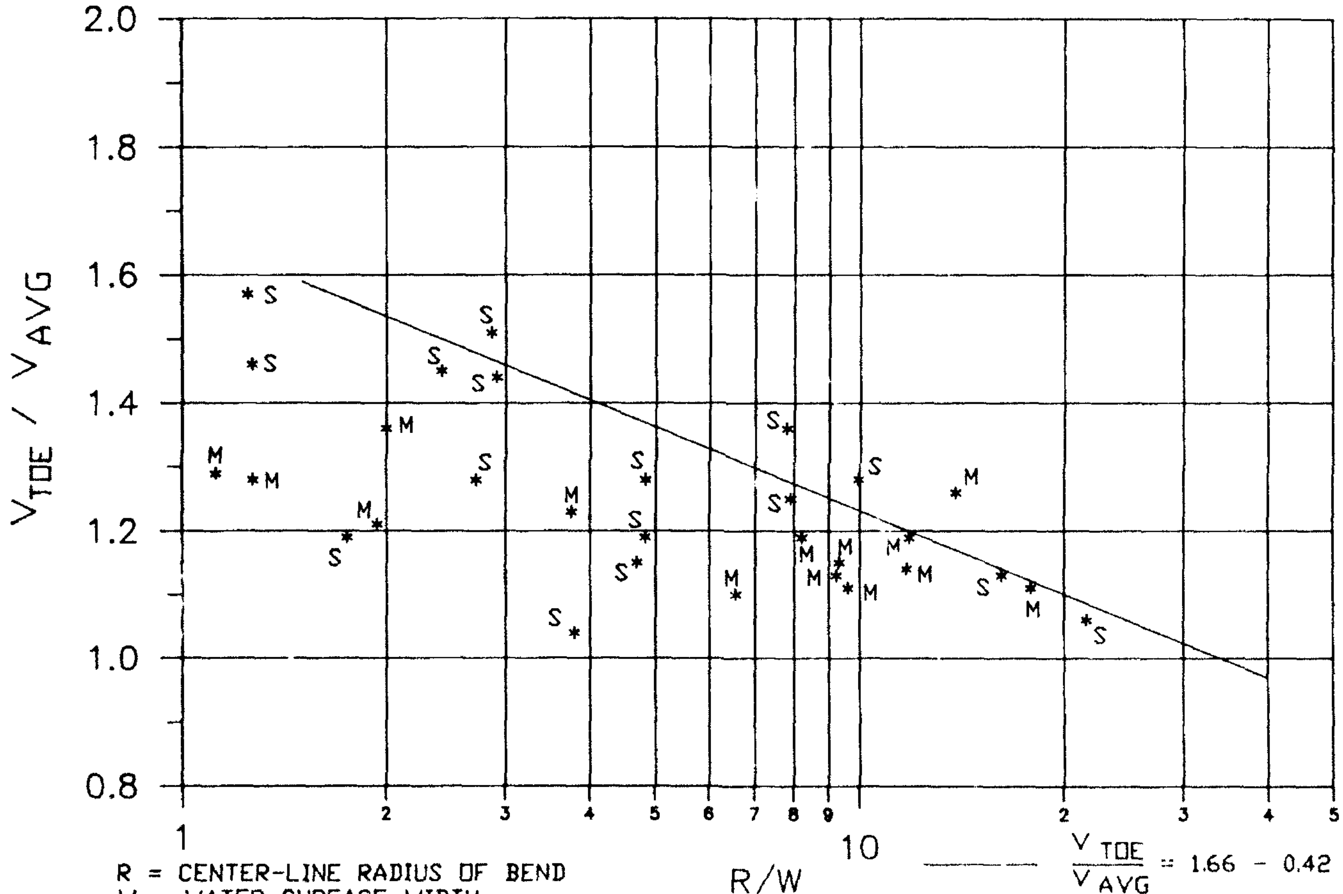
(Sheet 6 of 6)

Table 2
Bend Data

Bend Name	V_{avg} fps	Width ft	Arc Angle deg	Discharge cfs	Radius ft	MAX V_{nb} fps	MAX V_{20} fps
CT3	5.79	2,507	90	794,030	13,500	9.51	7.4
CT6	7.18	2,732	90	1,089,950	13,500	10.46	9.3
CT9	5.87	2,350	90	829,670	13,500	10.13	7.1
CT11	7.06	2,573	90	993,960	13,500	9.06	8.4
CT12	6.31	2,600	90	997,650	13,500	9.59	9.3
CT13	7.06	2,568	90	1,129,300	13,500	11.37	9
CY2	6.45	2,703	185	825,180	8,000	8.54	8.1
CY6	6.55	2,905	185	1,142,480	8,000	12.38	10
CY9	6.26	2,600	185	795,160	8,000	10.25	6.9
CY11	6.95	2,760	185	943,650	8,000	10	9
CY12	6.48	2,823	185	993,740	8,000	10.48	9.8
CY13	6.99	2,880	185	1,204,800	8,000	10.56	8
PR3	5.5	3,600	155	1,121,730	10,500	7.11	6.8
PR6	5.67	3,400	155	929,110	10,500	6.3	6.1
PR10	6.24	3,400	155	1,348,840	10,500	7.53	7.2
AR6	7.07	1,880	175	870,900	5,200	9.06	8.4
AR11	7.34	2,140	175	1,087,540	5,200	9.84	6.9
AR13	7	2,200	175	1,101,170	5,200	9.95	8.6
FT5	5.05	4,000	150	1,001,220	7,200	9.02	7.9
FT7	5.82	4,500	150	1,170,530	7,200	9.94	9.7
CO5	6.2	2,500	50	968,170	12,500	6.57	5.7
CO7	6.93	2,500	50	1,190,290	12,500	8.53	6.56
BL3	5.6	3,385	80	946,220	18,500	8.83	7.9
BL5	4.83	3,332	80	808,230	18,500	7.2	6.8
ML3	4.96	3,435	75	896,000	13,300	7.62	6.23
ML5	4.86	3,602	75	814,540	13,300	7.62	6.4
GG3	6.44	3,405	68	1,138,360	18,500	6.76	5.44
HS3	5.55	2,750	95	1,139,810	12,700	10.04	9
HS4	5.55	2,644	95	798,330	12,700	9.46	7.76

(Continued)

Table 2 (Concluded)							
Bend Name	V_{avg} fps	Width ft	Arc Angle deg	Discharge cfs	Radius ft	MAX V_{nb} fps	MAX V_{20} fps
WN3	5.41	4,250	26	1,038,950	25,500	8.42	6.6
WN4	6.62	4,500	26	1,255,230	25,500	9.06	7.4
WN7	5.41	4,000	26	851,890	25,500	7.73	7.3
KY3	6.07	2,600	83	782,130	12,500	7.62	6.7
KY4	6.93	2,640	83	823,300	12,500	7.67	6.4
MY6	6.09	3,100	70	1,033,380	13,000	7.68	7.1
MY9	4.91	2,500	70	843,330	13,000	8.19	8.1
BG3	5.47	3,640	175	1,102,670	6,500	8.76	8.03
LK1	5.47	2,800	135	756,560	10,700	6.23	4.93
LK4	6.11	3,500	135	1,168,500	10,700	7.33	6



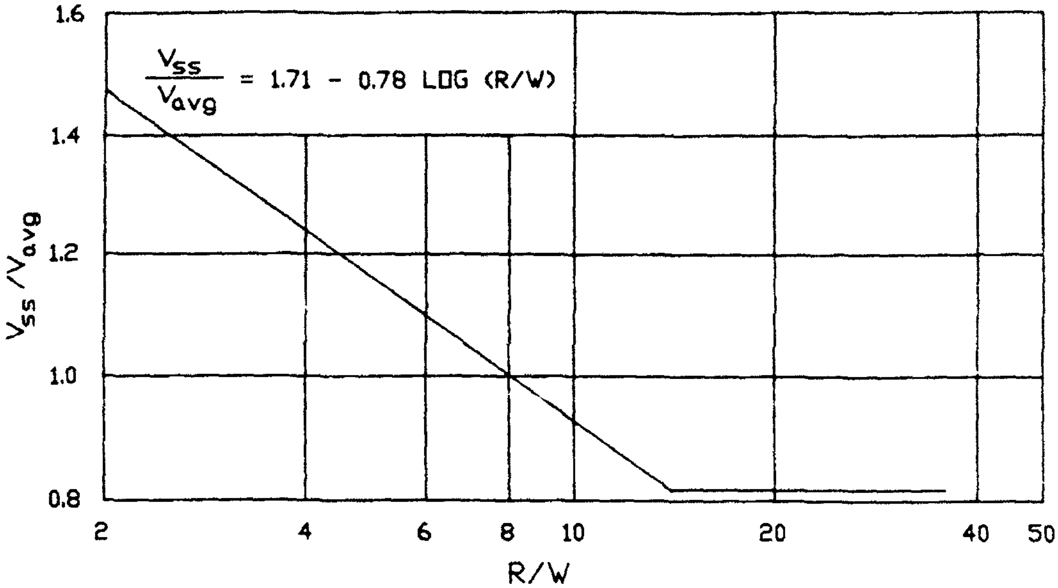
R = CENTER-LINE RADIUS OF BEND
W = WATER-SURFACE WIDTH
V_{TOE} = MAXIMUM VELOCITY IN BEND AT TOE OF SLOPE
V_{AVG} = AVERAGE CHANNEL VELOCITY
M = MEANDERING APPROACH CHANNEL
S = STRAIGHT APPROACH CHANNEL

———— $\frac{V_{TOE}}{V_{AVG}} = 1.66 - 0.42 \text{ LOG } (R/W)$

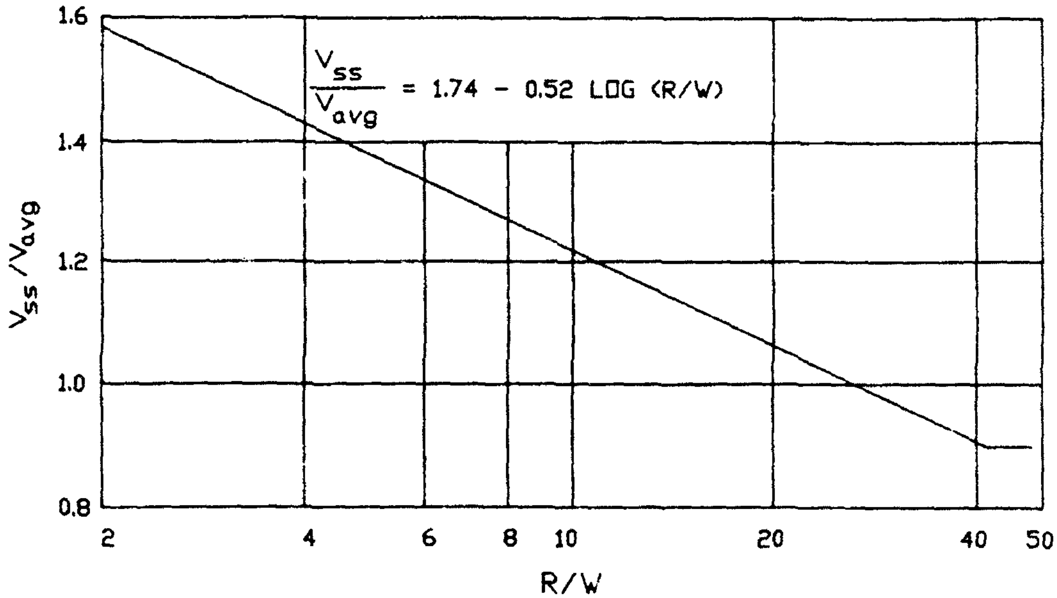
V_{TOE} / V_{AVG} VERSUS R/W

REPLOTTED FROM THORNE AND ABT(1990)

Plate 1



TRAPEZOIDAL CHANNEL

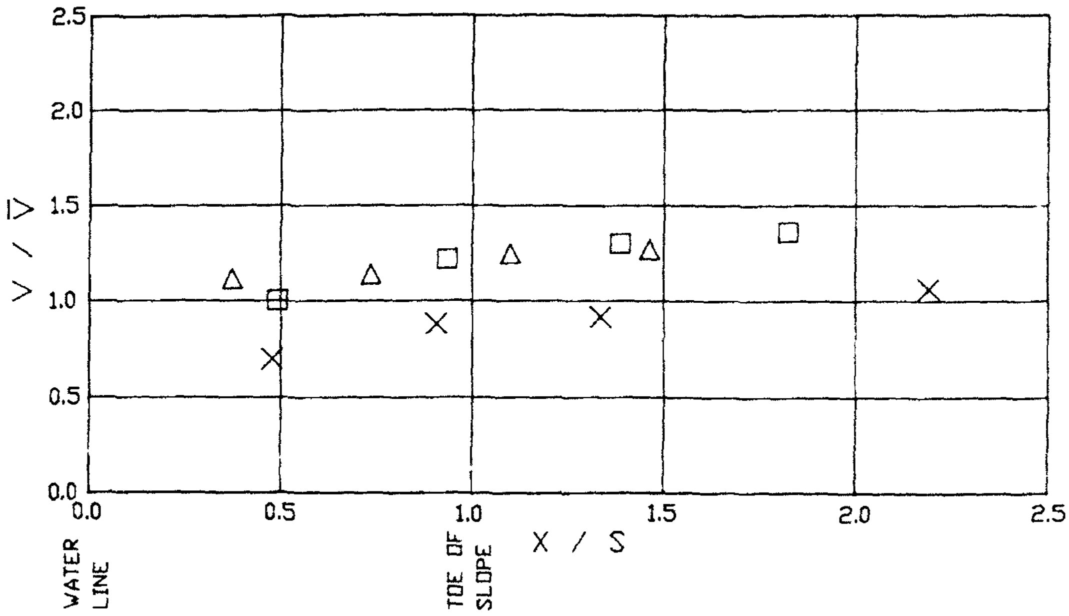


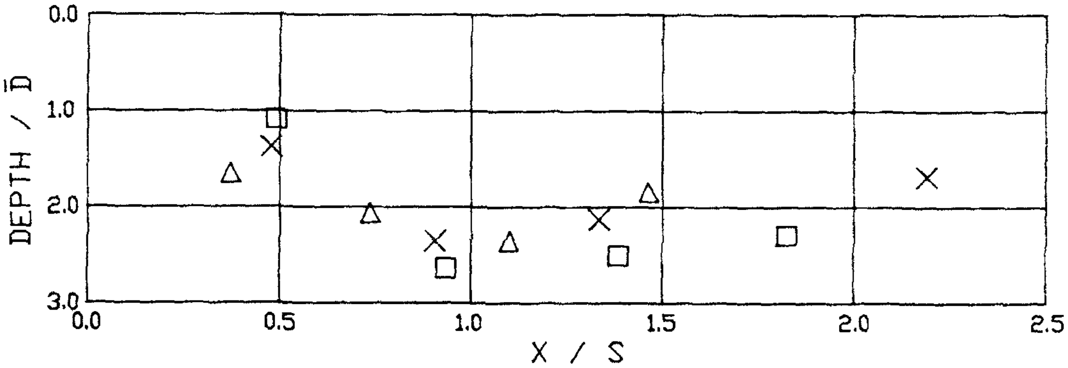
NATURAL CHANNEL

NOTE: V_{ss} IS DEPTH-AVERAGED VELOCITY AT 20 PERCENT OF SLOPE LENGTH UP FROM TOE

RIPRAP DESIGN VELOCITIES

(From EM 1110-2-1601)





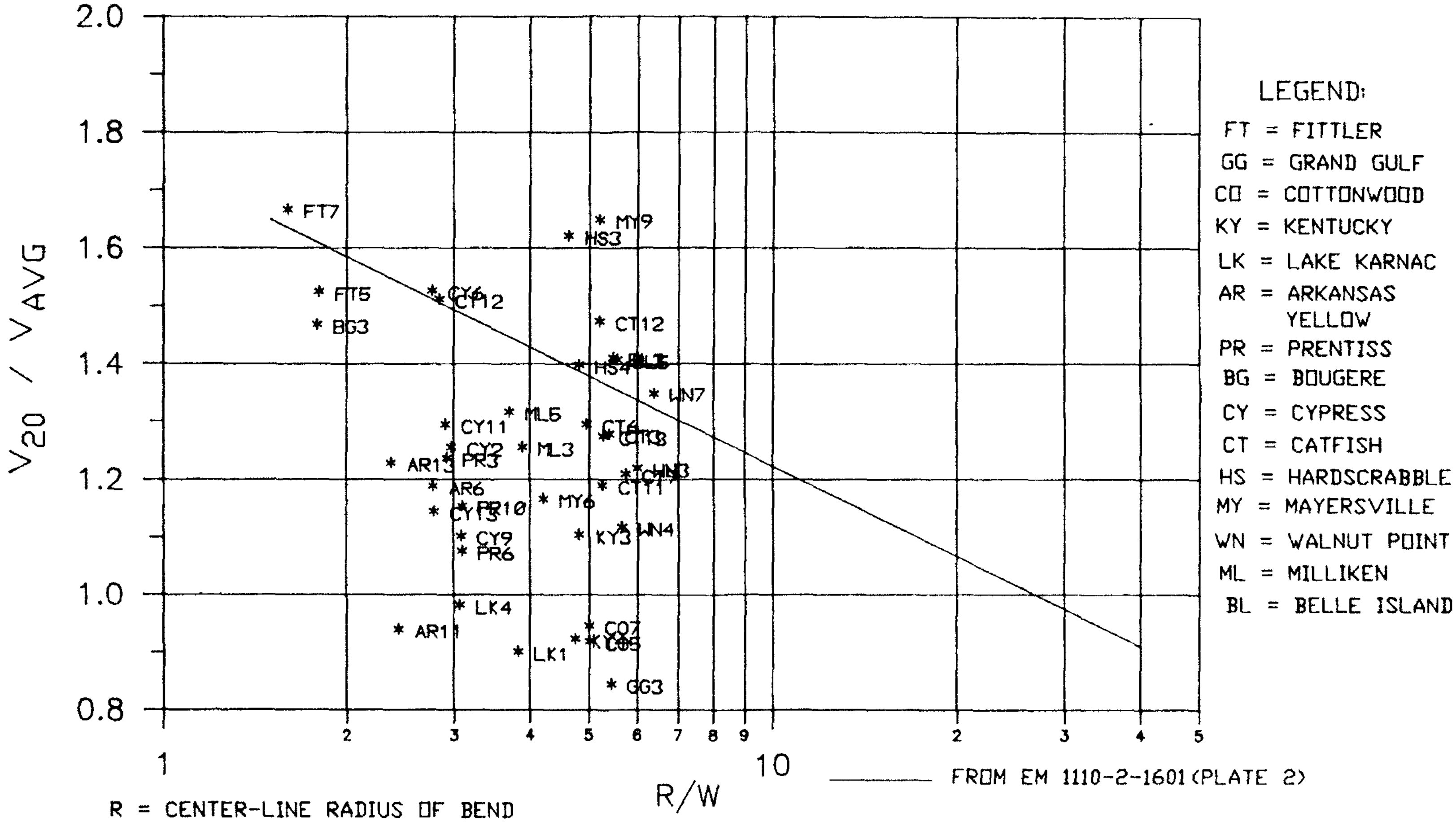
LEGEND

	SECTION	R/W	AR	$\bar{V}$	W	S	$\bar{D}$
×	476.6	1.28	163.0	4.85	5819	467	35.6
△	476.0	1.78	102.0	6.21	4197	550	40.8
□	475.2	2.01	97.9	6.59	3719	450	37.9

NOTE:

R = CENTER-LINE RADIUS OF BEND, FT
W = WATER-SURFACE WIDTH, FT
X = DISTANCE FROM WATERLINE, FT
S = DISTANCE FROM TOE TO WATERLINE, FT
AR = ASPECT RATIO = W^2/A
A = CROSS-SECTIONAL AREA, FT^2
V = DEPTH-AVERAGED VELOCITY, FPS
$\bar{V}$ = AVERAGE CHANNEL VELOCITY, FPS
$\bar{D}$ = A/W, FT

SIDE SLOPE VELOCITIES
MISSISSIPPI RIVER
FITLER COTTONWOOD 5
18-23 APRIL 1969



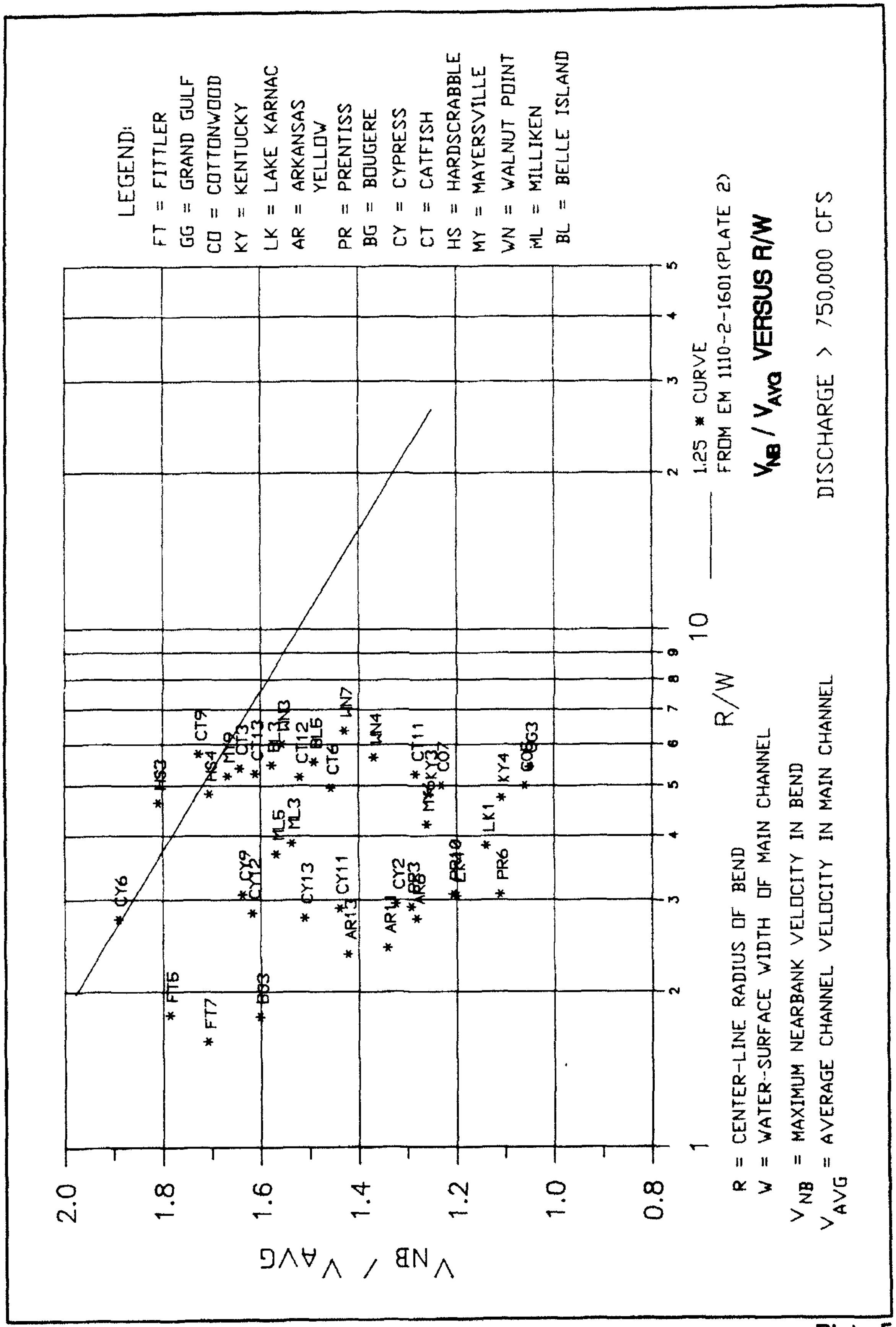
—— FROM EM 1110-2-1601 (PLATE 2)

R = CENTER-LINE RADIUS OF BEND
W = WATER-SURFACE WIDTH OF MAIN CHANNEL
V_{20} = MAXIMUM VELOCITY IN BEND AT 20 PERCENT UPSLOPE FROM TOE
V_{AVG} = AVERAGE CHANNEL VELOCITY IN MAIN CHANNEL

V_{20} / V_{AVG} VERSUS R/W

DISCHARGE > 750,000 CFS

Plate 4



LEGEND:
FT = FITTLER
GG = GRAND GULF
CO = COTTONWOOD
KY = KENTUCKY
LK = LAKE KARNAC
AR = ARKANSAS
YELLOW
PR = PRENTISS
BG = BOUGERE
CY = CYPRESS
CT = CATFISH
HS = HARDSCRABBLE
MY = MAYERSVILLE
WN = WALNUT POINT
ML = MILLIKEN
BL = BELLE ISLAND
1.25 * CURVE
FROM EM 1110-2-1601 (PLATE 2)
V_{NB} / V_{AVG} VERSUS R/W
DISCHARGE > 750,000 CFS
R/W
V_{NB} / V_{AVG}
R = CENTER-LINE RADIUS OF BEND
W = WATER-SURFACE WIDTH OF MAIN CHANNEL
V_{NB} = MAXIMUM NEARBANK VELOCITY IN BEND
V_{AVG} = AVERAGE CHANNEL VELOCITY IN MAIN CHANNEL

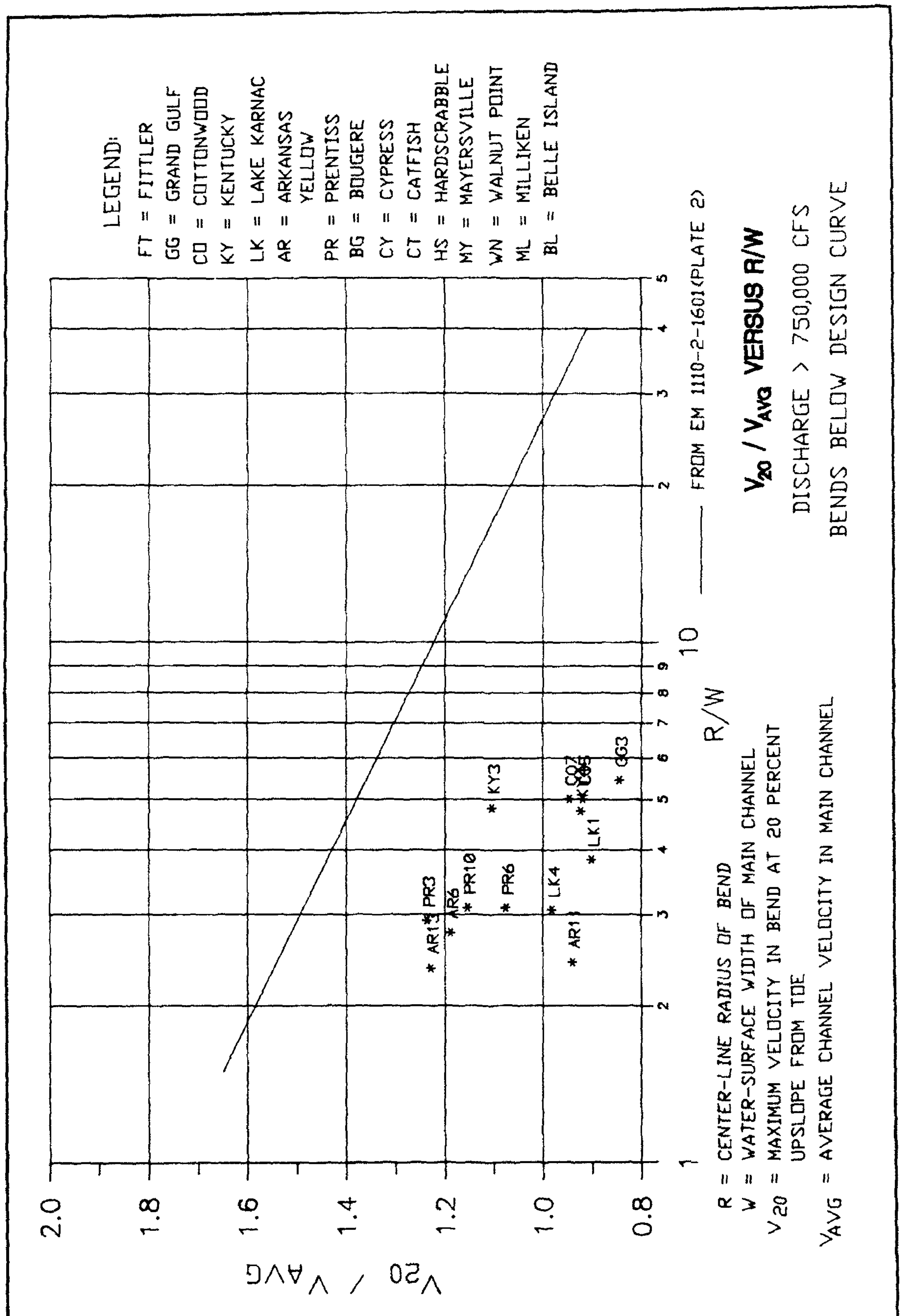
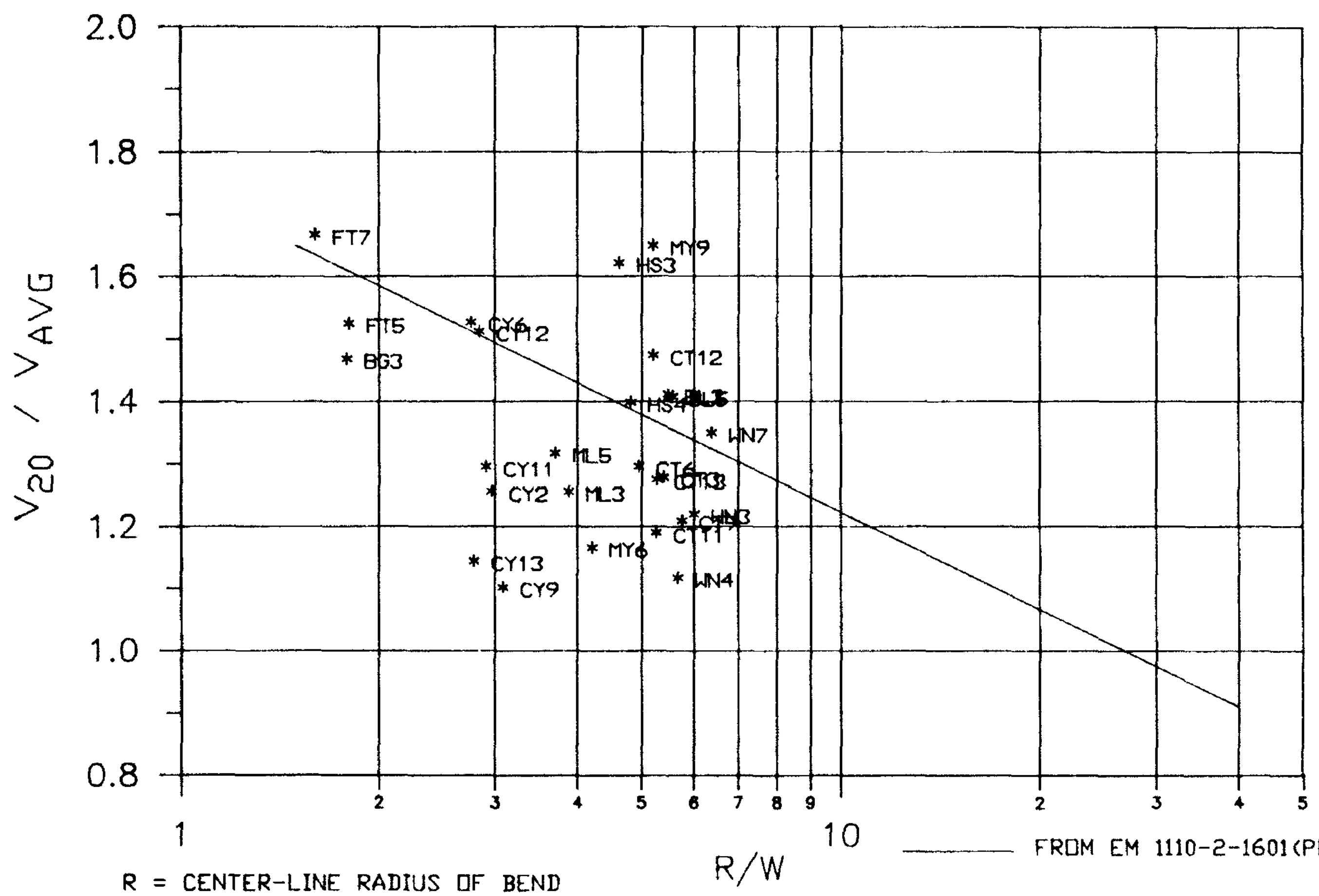

LEGEND:
FT = FITTLER
GG = GRAND GULF
CO = COTTONWOOD
KY = KENTUCKY
LK = LAKE KARNAC
AR = ARKANSAS YELLOW
PR = PRENTISS
BG = BOUGERE
CY = CYPRESS
CT = CATFISH
HS = HARDSCRABBLE
MY = MAYERSVILLE
WN = WALNUT POINT
ML = MILLIKEN
BL = BELLE ISLAND
FROM EM 1110-2-1601(PLATE 2)
V20 / VAVG VERSUS R/W
DISCHARGE > 750,000 CFS
BENDS BELOW DESIGN CURVE
R = CENTER-LINE RADIUS OF BEND
W = WATER-SURFACE WIDTH OF MAIN CHANNEL
V20 = MAXIMUM VELOCITY IN BEND AT 20 PERCENT UPSLOPE FROM TOE
VAVG = AVERAGE CHANNEL VELOCITY IN MAIN CHANNEL
V20 / VAVG
R/W
KY3
CO7
CO5
GG3
LK1
PR10
PR6
LK4
PR3
AR6
AR13
AR1

Plate 6



LEGEND:

FT = FITTLER
GG = GRAND GULF
CO = COTTONWOOD
KY = KENTUCKY
LK = LAKE KARNAC
AR = ARKANSAS YELLOW
PR = PRENTISS
BG = BOUGERE
CY = CYPRESS
CT = CATFISH
HS = HARDSCRABBLE
MY = MAYERSVILLE
WN = WALNUT POINT
ML = MILLIKEN
BL = BELLE ISLAND

——— FROM EM 1110-2-1601 (PLATE 2)

R = CENTER-LINE RADIUS OF BEND
W = WATER-SURFACE WIDTH OF MAIN CHANNEL
V_{20} = MAXIMUM VELOCITY IN BEND AT 20 PERCENT UPSLOPE FROM TOE
V_{AVG} = AVERAGE CHANNEL VELOCITY IN MAIN CHANNEL

V_{20} / V_{AVG} VERSUS R/W

DISCHARGE > 750,000 CFS
BENDS NEAR DESIGN CURVE

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Maximum depth-averaged velocities measured along protected bends of the Mississippi River were compared with a predictive relation used in riprap design. The predictive relation provided a conservative estimate with the observed velocities for most of the bends. The data exhibited significant scatter, and the effects of factors such as bend angle and bend type were not apparent in the data.

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